Status Report No. 5

NOISE INVESTIGATIONS WITH IMPINGING JET FLOWS

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submitted to

National Aeronautics and Space Administration
Grant No. NsG-431

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Report No. ME-1085-651205

December 1965

Summary

Experimental investigations of the noise from interacting high speed jet flows show that the total acoustic power radiated peaks between 5 to 10 per cent control for a certain range of control jet impingement point locations and then decreases with increasing percent control, to a value not much higher than that for the power jet with no control flow added. For still higher percent control, the acoustic power increases again to values which even at 50 percent control are not significantly different from the peak values occurring between 5 and 10 percent control. This interesting behavior of radiated acoustic power is examined with reference to marked changes in shock structure of the underexpanded jet flow as evidenced in shadowgraphs recorded at different percent control values. The experimental data showing changes in the directivity of the noise field of the interacting jet flows with increase in percent control are also presented.

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Introduction

This biannual Status Report No. 5 covers the period from June 1, 1965 to November 30, 1965 on Noise Investigations with Impinging Jet Flows being conducted at Syracuse University under NASA Grant No. NsG-431.

The original air flow control system permitted a maximum control jet stagnation pressure of 30 psig, but early in the experimental program it became clear that the 30 psig maximum pressure covered only a portion of the range of operating conditions in which interesting phenomena were to be observed. Consequently, changes were made in the air flow control system to increase the maximum possible control jet pressure. These consisted of making provision to isolate the control jet pressure controller (maximum pressure - 30 psig) from the air control system, and installing piping which draws air for the control jet from the controlled air of the power jet through a manually operated valve. This arrangement now permits control jet pressures up to 50 psig, being limited only by the range of the precision pressure gage employed to measure this pressure. It also means that control jet pressure stabilization is not independent but is a consequence of power jet pressure stabilization, thus simplifying the experimental procedure. Furthermore, this arrangement insures that percent control (defined as 100 times the ratio of control jet stagnation gage pressure to power jet stagnation gage pressure) once set is subject to negligible error as the power jet operates within the prescribed tolerance of $\pm$ 0.25 psi. This is so since the control jet pressure error is proportional to the power jet error and these errors have little effect on the value of the ratio of control jet pressure to power jet pressure.

To minimize upstream valve and piping noise in the power and control jet settling tanks, mufflers, utilizing baffles and steel wool, were installed at the air inlet end of each settling tank which were specifically designed to house these mufflers.

Sound Field Directivity Data

Two control jet nozzles have been fabricated with different values of impingement angle α (defined as the acute angle between the power jet nozzle axis and the axis of the generatrix of the annular control jet nozzle). These are denoted as control jet nozzle No. 1 for $\alpha = 90°$, and control jet nozzle No. 2 for $\alpha = 45°$. The interacting jet nozzle arrangement with control jet nozzle No. 1 is illustrated in Fig. 1. The power jet nozzle exit diameter is 3/8" and the control jet exit is 3/4" in diameter and 3/64" wide making its exit area equal to that of the power jet. The impingement point of the control jet on the power jet is variable, and is characterized by the ratio x/D where x is the distance from the plane of the power jet exit to the centroid of the annular control jet exit area, and D is the power jet diameter.

Using each of the two control jet nozzle arrangements, considerable noise directivity data (SPL versus θ measured from downstream jet axis) for the interacting jets has been obtained in the anechoic chamber (for details of the anechoic chamber see Status Report No. 4) for various conditions of percent control and x/D ratio. Power jet stagnation pressure was kept at 100 $\pm$ 0.25 psig, while control jet stagnation pressure was varied from 0 to 50 psig for x/D ratios between 0.2 and 1.0. Sound pressure levels were measured at a radius of 72.0 inches using a Bruel and Kjaer 4135 quarter-inch microphone and 2604 microphone amplifier. The sensitivity of the microphone was regularly checked with the Bruel and Kjaer pistonphone.

Because of the copious directivity data, a Fortran program was written for mechanically plotting the data with the Calcomp plotter available at the Syracuse University Computing Center. This program utilizes the same data cards prepared for another Fortran program which is discussed below. These plots permit observation at a glance of the effects of jet operating conditions on directivity of the sound field. Typical pages of plotted data are reproduced as Figs. 2a,b,c. These are discussed later.

Total Acoustic Power Radiated

Using the directivity data mentioned above, the total acoustic power radiated by the interacting jets under different operating conditions was computed based on the following analysis:

Consider an imaginary sphere of radius R enclosing the interacting jets which are at the sphere center. The SPL on the sphere is a function only of azimuth angle θ measured from the downstream jet axis. By measuring the SPL at small increments $\Delta\theta$ of azimuth angle around the interacting jets and determining the sound intensity which is taken to be constant on the annular surface around the jet axis of width $R\Delta\theta$, the total acoustic power radiated can be determined by summing these intensities on the incremental surface elements of the sphere between 0° and 180°.

Let $180°/\Delta\theta$ be an integral value q, so that there are q + 1 SPL measuring stations from 0° to 180°, numbered consecutively from 0 to q starting at $\theta = 0$. The azimuth angle of the i^{th} station where SPL_i is measured is $i\Delta\theta$. This angle locates an elemental annular area A_i of width $\Delta\theta$ bounded by $i\Delta\theta \pm \Delta\theta/2$. It then follows that the incremental areas

$$A_i = 4\pi R^2 \sin i\Delta\theta \sin \frac{\Delta\theta}{2} \quad , i = 1, 2, \ldots, q-1$$

and the polar areas at $\theta = 0, 180°$

$$A_o = A_q = 2\pi R^2 [1 - \cos \frac{\Delta\theta}{2}] \quad .$$

Letting p_i denote the acoustic pressure at station i, the total acoustic power radiated by the jet flow is

$$P_t = \sum_{i=0}^{q} \frac{p_i^2}{\rho_o c_o}$$

with proper attention to units where $\rho_o c_o$ is the characteristic impedance of air. From the definition of SPL re 0.0002 dyne/cm^2, obtain

$$p_i^2 = 4 \times 10^{-8} \text{ antilog } \left(\frac{SPL_i}{10}\right) \qquad \left[\frac{\text{dynes}}{\text{cm}^2}\right]^2$$

and noting that

$$1 \text{ watt} = 10^7 \frac{\text{dyne - cm}}{\text{sec}}$$

obtain

$$P_t = \frac{4 \times 10^{-15}}{\rho_o c_o} \sum_{i=0}^{q} \text{antilog } \left(\frac{SPL_i}{10}\right) A_i \qquad [\text{watts}]$$

where $\rho_o c_o$ is in cgs units and A_i is in cm^2. Finally, expressing this as power level, PWL re 10^{-13} watt, obtain

$$PWL = 10 \log \left[\frac{4 \times 10^{-2}}{\rho_o c_o} \sum_{i=0}^{q} \text{antilog } \left(\frac{SPL_i}{10}\right) A_i\right] \text{ db}$$

The minimum value of θ for taking SPL measurements which were not influenced by jet flow impingement on the microphone was found experimentally to be 15°. Also, increasing the measuring radius to insure far field measurements necessitates a decrease in the maximum value of θ, and vice versa, because of the confines of the anechoic chamber. For R = 72.0 inches, the maximum azimuth angle is 120°. Beyond that, measurements would be in the shadow of the settling tank and control jet nozzles.

Restricting measurements to between 15° and 120° changes the limits on the previous summation to

$$m \geq \frac{15°}{\Delta\theta}$$

and

$$n \leq \frac{120°}{\Delta\theta}$$

for the lower and upper limits respectively, where m and n are integers. These conditions eliminate consideration of the polar areas, leaving as a final working expression, after substitution of the expression for A_i,

$$PWL = 10 \log \left[\frac{16 \times 10^{-2}}{\rho_o c_o} \pi R^2 \sin \frac{\Delta\theta}{2} \sum_{i=m}^{n} \sin i\Delta\theta \text{ antilog } \left(\frac{SPL_i}{10}\right)\right] \text{ db.}$$

A Fortran program was written to compute PWL using the foregoing equation. The bulk of data taken to date has been with R = 72.0 inches, $\Delta\theta = 15°$, m = 1, and n = 8, although these are not fixed and can be varied as circumstances dictate. The angle increment $\Delta\theta$ may be as small as 1°. The results of these computations were prepared as a series of curves of PWL versus percent control for various x/D ratios. Typical results are given in Fig. 5.

Discussion of Experimental Results

Three plots of PWL versus percent control for control nozzle No. 1 at x/D ratios of approximately 0.4, 0.6, and 0.8 are reproduced in Fig. 3.

The increase of PWL with the first few percent control was not unexpected as such a behavior was noted in earlier preliminary observations by the authors with interacting two-dimensional jets. Also the likelihood of increased turbulent mixing of these two interacting jet flows would be expected to cause an increase in noise. However, between 5 and 10 percent control the total acoustic power radiated peaks and then begins to drop, eventually reaching a relative minimum value not much higher than that of the power jet with no control flow added.

The PWL then increases again with a further increase in percent control and demonstrates a slight but definite perturbation at about 35 or 40 percent control. From zero to 10 percent control the power radiated increases at a rate of approximately one db per percent control, but from 10 percent control to 50 percent control the total acoustic power increase is not more than $1\frac{1}{2}$ decibels. This PWL variation with percent control is found to occur for approximately $0.2 < x/D < 0.8$. These observed variations in the acoustic power indicate a dependence on the interacting jet operating parameters and geometry which when fully investigated may be useful in evolving new methods of jet noise abatement. As it is evident from the plots of PWL versus percent control (Fig. 3), the peak value of PWL for each of the three curves decreases and occurs at slightly higher percent control as x/D decreases. Also, the minimum value of PWL attained at non-zero percent control occurs at higher percent control with decreasing x/D ratio.

It has been observed and reported earlier (Status Report No. 4) that the addition of the control flow serves to diminish the Riemann disc while lengthening the reflected shocks, and it eventually results in the emergence from the reflected shocks of a new oblique shock structure which separates from the original reflected shock structure and moves downstream with increasing percent control. A sequence of shadowgraphs corresponding closely to the conditions of the plot of PWL versus percent control of Fig. 3 for $x/D = 0.4013$ is reproduced as Fig. 4 and shows this progression of shock structure change with percent control.

A shadowgraph of the power jet operating at 100 psig with no control flow impingement exhibits the usual shock structure for a highly underexpanded choked jet (Fig. 4a). As percent control increases, the intercepting shocks move inward, diminishing the extent of the normal shock disc and lengthening the reflected shocks. As this is happening, the total power radiated by the interacting jets is increasing (point b Fig. 3) and Fig. 4b shows the flow condition at 5 percent control. As percent control increases further, the intercepting shocks meet, eliminating the normal shock disc. Following this, new oblique shocks emerge from the original reflected shocks and begin to move in the downstream direction as percent control increases further. Corresponding to these changes in the flow, the total acoustic power radiated rises to a peak of about 148 db re 10^{-13} watt and then begins to decrease. Figure 4c is a shadowgraph of the flow at 10 percent control at which the new oblique shock structure (labelled) has already been created and has moved slightly downstream. This condition corresponds to the point c on the plog of Fig. 3 slightly to the right of the PWL peak. The question naturally arises as to whether the PWL peaks at the condition where the intercepting shocks just come together. This point remains to be established and will be closely examined.

As percent control is increased still further, the new oblique shocks move further downstream and the corresponding acoustic power radiated decreases to a minimum of approximately 144 db and then increases. Figure 4d shows the oblique shock positions near the minimum PWL condition. No shadowgraphs are presently available at the condition of the PWL perturbation near 35 percent control as these shadowgraphs were taken prior to the acoustic measurements when 30 percent control was the maximum attainable. Shadowgraphs at these operating conditions will be obtained in the near future.

Plots of the directivity data of the interacting jets for $x/D = 0.4013$ are given as Figs. 2a,b and c. These are plots of SPL versus azimuth angle θ for 2 psi increments of control jet pressure. The identifying information for each plot is located immediately under each axis and the value of percent control for each condition is numerically equal to P_{OP} since in all cases the power jet operating pressure is 100 psig. All other information listed identifies the data as having been measured at a radius of 72.00 inches with control jet nozzle No. 1 at $x/D = 0.4013$. These plots graphically illustrate the changes that are occurring in the directivity of the radiated sound with control jet flow impingement.

In general, for all conditions of percent control, with the exception of zero percent control and the value of percent control at which the acoustic power is a minimum, a secondary peak in SPL appears in addition to the peak normally observed in jet flows near 30°. At the highest percent control values, this secondary peak occurs at 60° and exceeds the peak at 30°.

Future Plans

Experimental data are currently being gathered for evaluation of the total acoustic power radiated by the interacting jets using control jet nozzle No. 2. Following completion of this phase of the investigation, 1/3 octave spectrum analysis will be carried out on the interacting jet noise field using both control jet nozzles, during which the tape system pruchased earlier (see Status Report No. 3) will be utilized as required. A malfunction in the tape transport which was discovered soon after it was delivered has been satisfactorily corrected by the manufacturer. The need to return the system to the manufacturer for correction resulted in some delay in making the system operational.

Following these acoustical investigations, additional systematic optical investigations will be undertaken with careful attention to shock spacing and geometry and their relation to previously discussed phenomena, as well as to spectral emission characteristics.

Plans are also being made to investigate interacting jets similar to those described herein, but with free entrainment allowed for the power jet and control jet flows. Reference to Fig. 1 shows that no free entrainment is possible upstream of the control jet, and also that the control jet nozzle forms a cavity from which the power jet emerges. The planned nozzles will permit evaluation of the effects of the cavity so formed on the sound field. The present nozzle arrangement does not permit operation of the control jet alone since the control jet entrains air from the power jet nozzle and settling tank and causes a pulsating flow condition. The planned nozzle arrangement will eliminate this problem and permit noise investigation of the control jet alone. This will allow a comparison of the interacting jet noise field with the noise fields of the power and control jets separately.

Publications

A letter to the editor entitled "Noise from Impinging, Two Dimensional, Underexpanded Jet Flows," by William J. Sheeran and Darshan S. Dosanjh reporting some observations made in relation to these investigations appeared in the Journal of the Acoustical Society of America, Vol. 38, No. 3, pp. 482-484, September 1965.

It is the authors'expectation that the next status report will include a sufficiently self-contained body of useful information on noise from interacting jet flows to justify its submittal to NASA in the form of a technical note for publication.

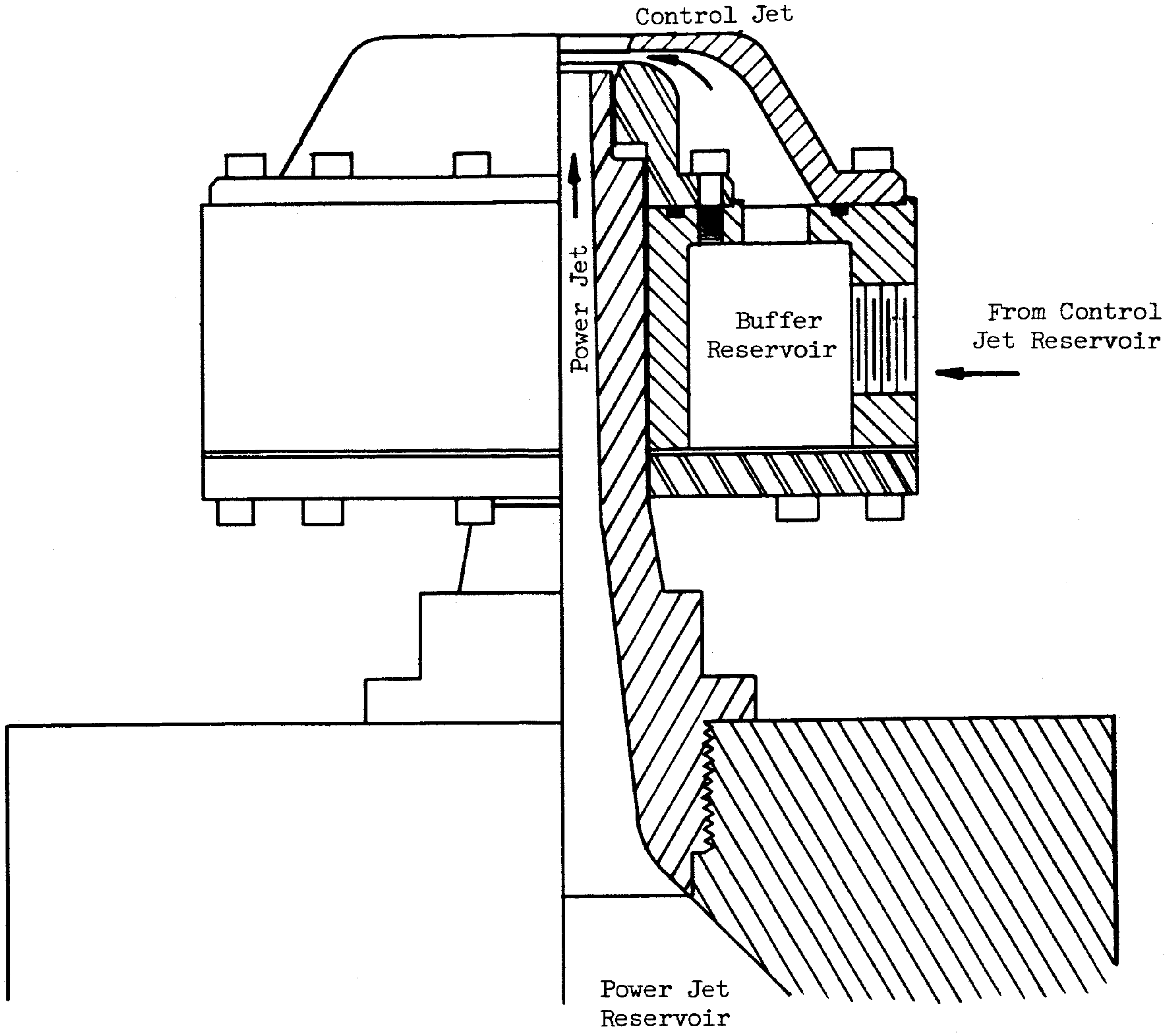


Fig. 1 POWER AND CONTROL JET NOZZLE ASSEMBLY

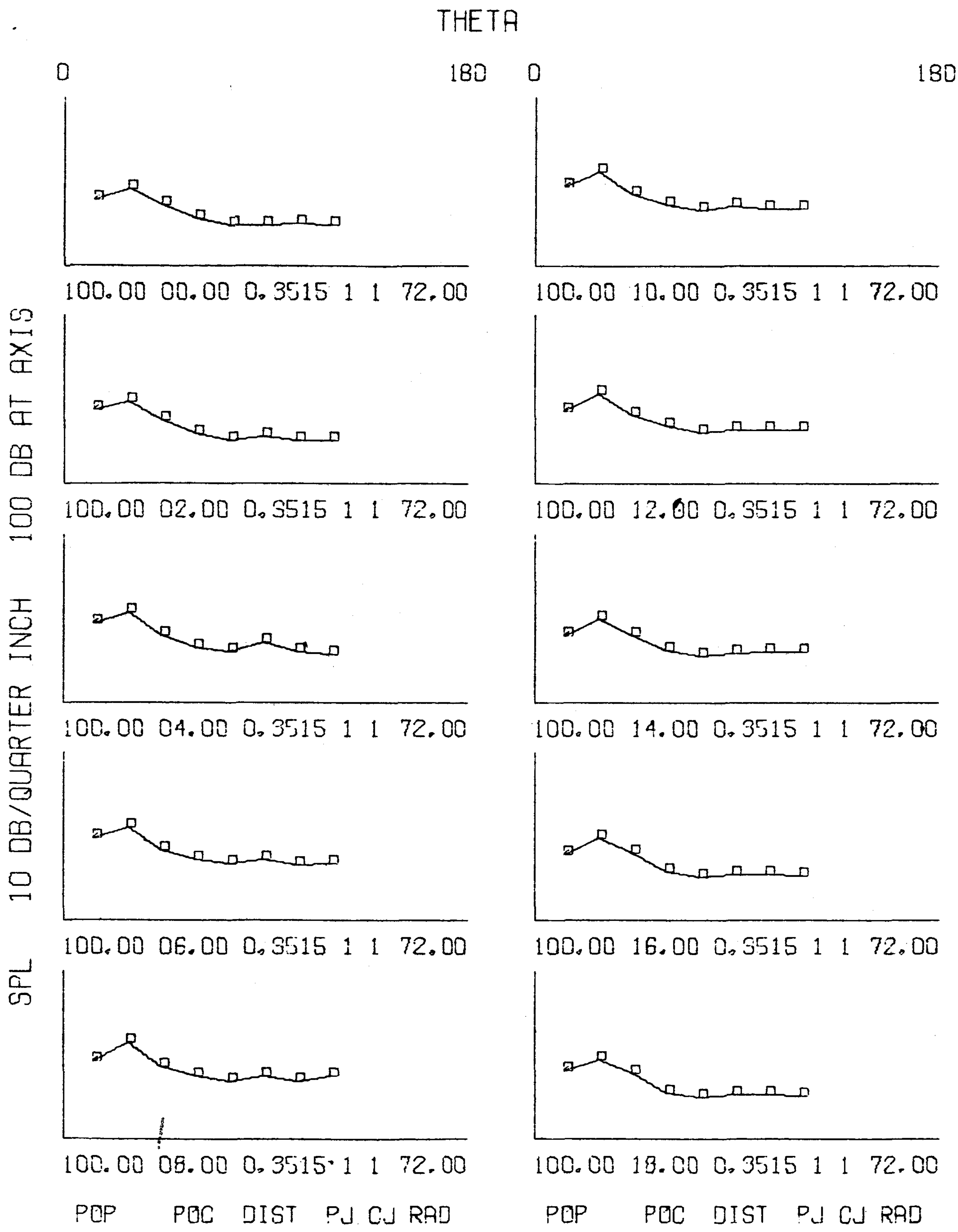


Fig. 2a SOUND PRESSURE LEVEL (SPL re 0.0002 μbar) versus AZIMUTH ANGLE θ

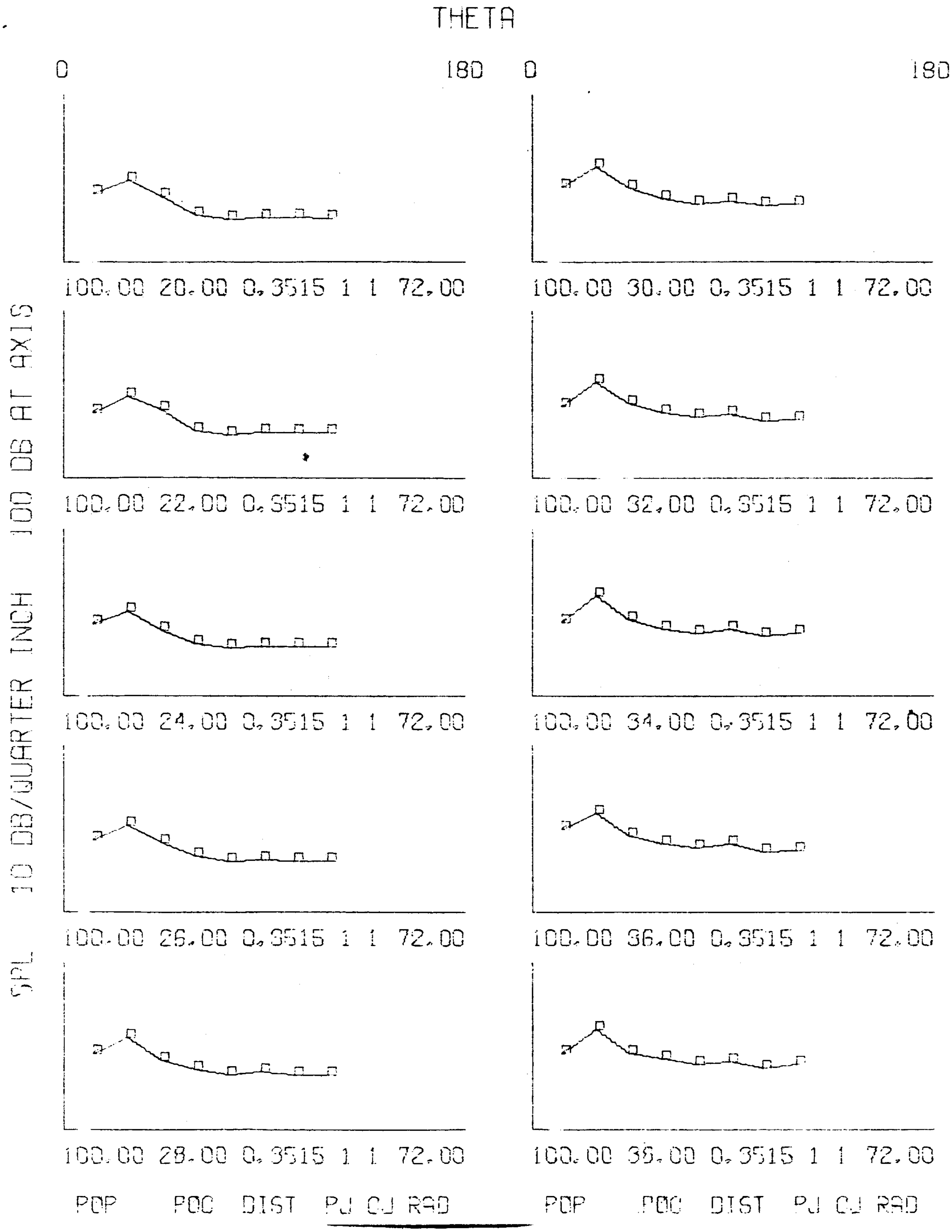


Fig. 2b SOUND PRESSURE LEVEL (SPL re 0.0002 μbar) versus AZIMUTH ANGLE θ

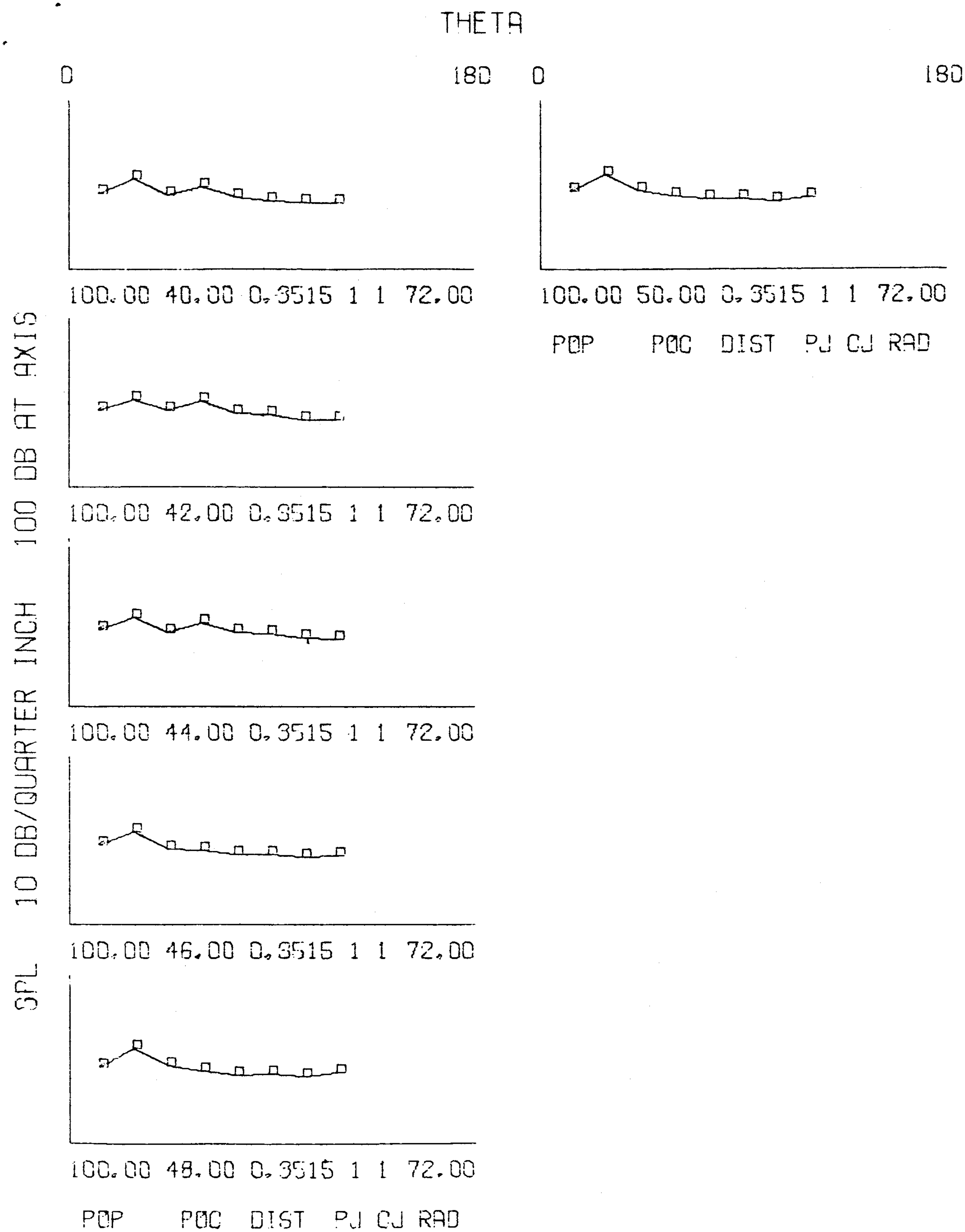


Fig. 2c SOUND PRESSURE LEVEL (SPL re 0.0002 μbar) versus AZIMUTH ANGLE θ

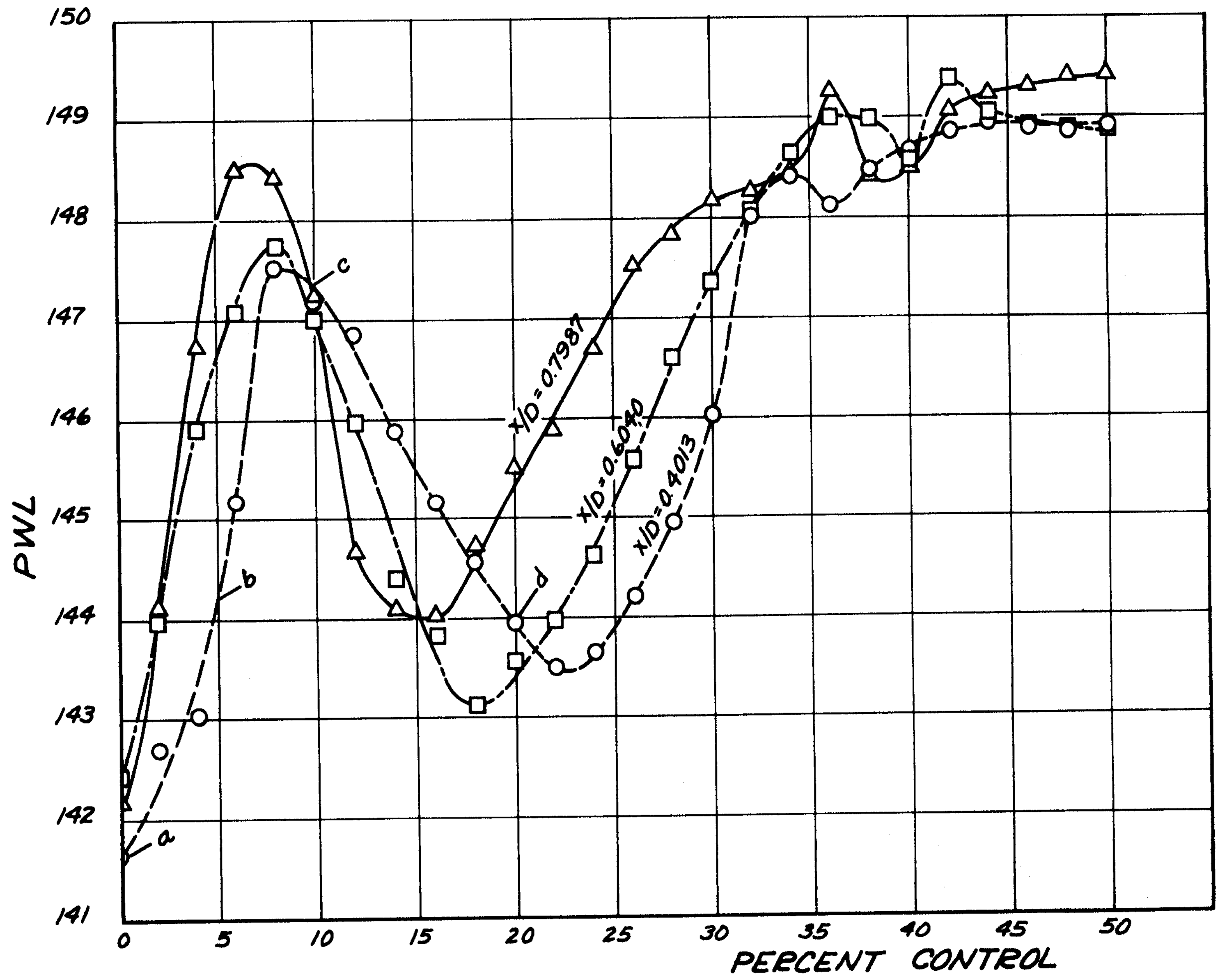
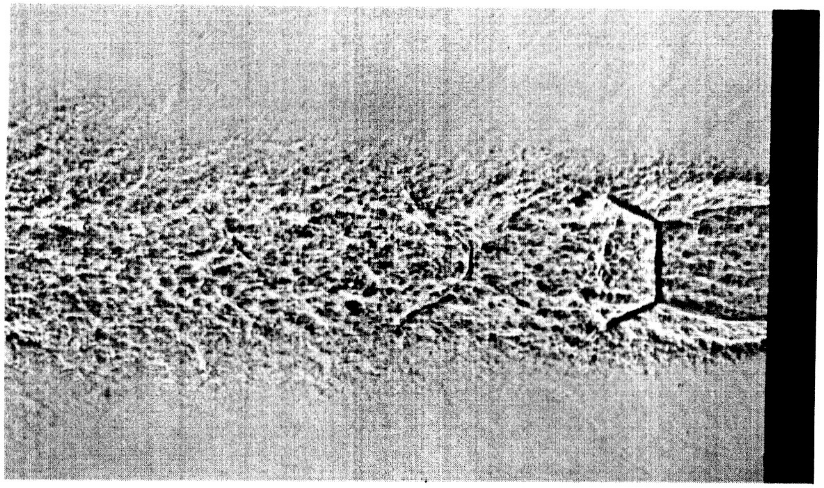
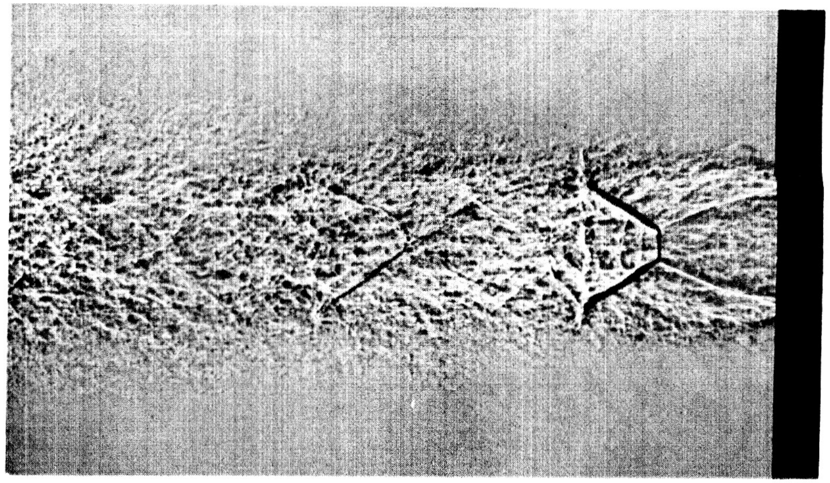


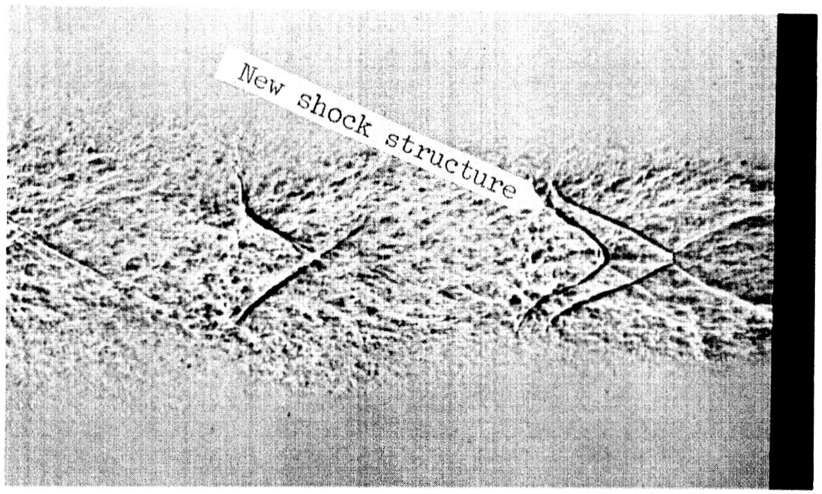
Fig. 3 TOTAL ACOUSTIC POWER (PWL re 10^{-13} watt) versus PERCENT CONTROL. Points a, b, c, d correspond to the operating conditions of Figs. 4a, b, c, d respectively.



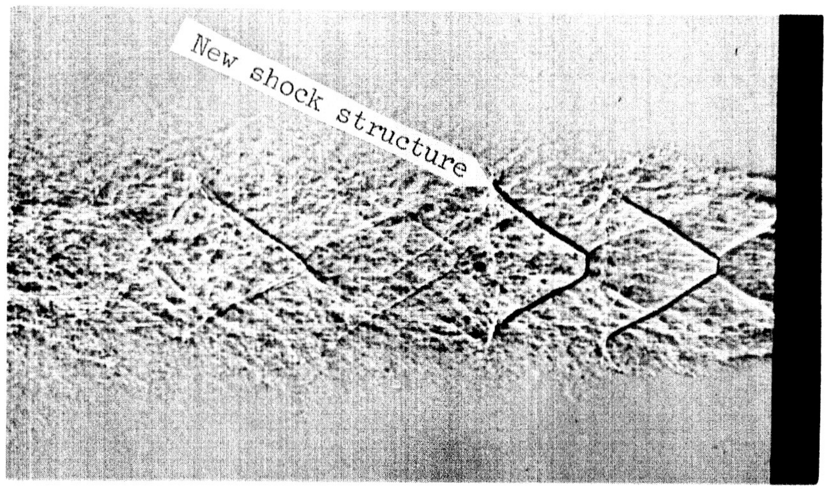
(a) Zero percent control



(b) Five percent control



(c) Fifteen percent control



(d) Twenty percent control

Fig. 4 Shadowgraphs of interacting jet flows at $x/D = 0.396$
Power jet stagnation pressure = 100 psig.